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Automatic Control of a 0.3 m Cryogenic Test Facility

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Studies have been undertaken to mathematically model the cryogenic wind-tunnel process, validate the model by the use of experimental data from the 0.3 m transonic cryogenic tunnel, and construct an interactive simulator of the cryogenic tunnel using the validated model. Additionally, this model has been used for designing closed-loop feedback control laws for regulation of temperature and pressure in the 0.3 m transonic cryogenic tunnel. The global mathematical model of the cryogenic tunnel that has been developed consists of coupled nonlinear differential governing equations based on an energy state concept of the physical cryogenic phenomena. Process equations and comparisons between actual and computer simulation predictions of tunnel response are given. Also included are the control laws and simulator and tunnel responses obtained using the feedback schemes for closed-loop control of temperature and pressure. These data show that the microprocessor-based proportional-integral control laws for pressure and temperature regulation have yielded very good closed-loop results.

Nomenclature

A	= area, m^2 or percent of valve opening
b	= pressure loss coefficient
c_m	= specific heat of metal, J/kg-K
c_p	= specific heat of gas at constant pressure, J/kg-K
c_v	= specific heat of gas at constant volume, J/kg-K
D	= dimensionality constant
E	= internal energy, J
GN_2	= gaseous nitrogen
K	= gain
LN_2	= liquid nitrogen
$\dot{m}$	= mass flow rate, kg/s
M	= Mach number
N	= fan speed, rpm
p	= total pressure, atm
$\dot{Q}$	= heat flow, J/s
r	= pressure ratio
s	= Laplacian mathematical operator
t	= time and time constant, s
T	= total temperature, K
V	= volume, m^3
W	= mass, kg
α	= cooling capacity of gaseous nitrogen, J/kg
β	= cooling capacity of liquid nitrogen, J/kg
θ	= thermal mass, J/K
τ	= transport time lag, s
η	= fan efficiency
γ	= ratio of specific heats

Subscripts

a	= acoustic
c	= tunnel circuit
F	= fan
G	= gas
L	= liquid
m	= metal

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Introduction

EXPERIENCE during the past six years of operation of the NASA Langley Research Center 0.3 m transonic cryogenic tunnel (TCT) has shown that there are problems associated with efficient operation and control of cryogenic tunnels using manual control schemes. This is due to the high degree of process cross-coupling between the independent control variables (temperature, pressure, and fan drive speed) and the desired test condition (Mach number and Reynolds number). One problem has been the inability to maintain long-term accurate control of the test parameters. Additionally, the time required to change from one test condition to another has proven to be excessively long and much less efficient than desirable in terms of liquid nitrogen and electrical power usage. For these reasons, studies have been undertaken to: 1) develop and validate a mathematical model of the 0.3 m cryogenic tunnel process, 2) utilize this model in a hybrid computer simulation to design temperature and pressure feedback control laws, and 3) evaluate the adequacy of these control schemes by analysis of closed-loop experimental data. This paper will present the results of these studies.

System Development

Throughout this system development, the objectives have been to improve the quality of the test data by maintaining tighter control of the test conditions, and to decrease the operating costs by reducing the amount of time and hence the amount of liquid nitrogen required for a given amount of testing. In theory, both of these objectives can be achieved through implementation of precise closed-loop automatic regulation and control of the tunnel variables. The approach taken has led to the development of a global mathematical model of the tunnel process, development of a real-time hybrid computer simulator, and development of control laws designed to maintain temperature to within ± 0.25 K, pressure to within ± 0.25 psia, and Mach number to within ± 0.002. Presently, the control laws are implemented in dedicated microprocessors for control of both temperature and pressure in the 0.3 m tunnel. Closed-loop experimental data are presented herein to show results achieved using these proportional-integral-derivative temperature and pressure control designs.

It was recognized early in this work that experimental data would be required to validate the derived process model, and therefore, the first phase of work was to obtain data on the dynamic response of temperature, pressure, and Mach

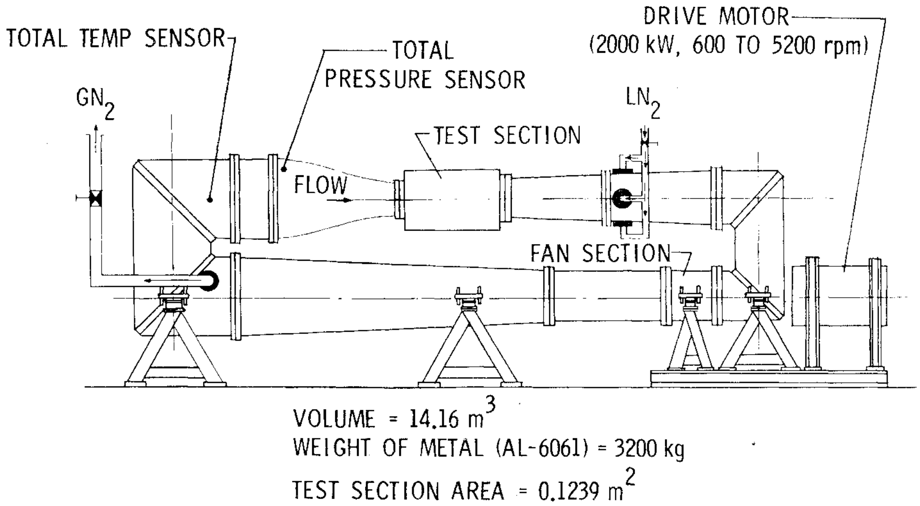

Fig. 1 0.3 m TCT control configuration.

number to step changes of the input variables throughout the tunnel operational envelope. Figure 1 shows the 0.3 m tunnel control configuration for these response tests. Principal control system inputs are liquid nitrogen injected rate, gaseous nitrogen exhaust rate, and fan speed. Both the liquid nitrogen and gaseous nitrogen flow rates are manually controlled by commands to specifically designed digital valves, through which step inputs to the injection or exhaust systems were realized by pulsing a selected element of the appropriate digital valve. Mach number dynamics were determined by means of a 100 rpm step change in speed of the fan drive motor. Total temperature, total pressure, and Mach number, as well as the three input commands, were recorded at a rate of 40 samples/s.

In constructing the math model of the cryogenic process, well-known fundamental physical equations describing the behavior of nitrogen in a closed-circuit wind tunnel were utilized. The first law of thermodynamics for determining the time rate of change of the internal energy for the cryogenic nitrogen gas is expressed as:

$\dot{E}$ = heat from the tunnel metal

+ heat of compression from the fan

+ heat from injection of LN_2

+ heat from exhaust of GN_2

After mathematical manipulation, adding the transport delays involved in the measurements, and using

$$\dot{Q}_m = W_m c_m Ts/(1+t_m s)$$

$$\dot{Q}_F = K_F p M^3 (1+0.2M^2)^{-3}\sqrt{T}$$

$$K_F = \frac{6965}{\eta} A c_p b \frac{\gamma-1}{\gamma}$$

$$\dot{m}_L = K_L A_L = 3.47\sqrt{p_L - p}A_L$$

$$\dot{m}_G = K_G \frac{p}{\sqrt{T}} A_G = 21.8\left[2-\left(\frac{1.5}{p}\right)^{1.7}\right]\frac{p}{\sqrt{T}}A_G$$

$$\alpha = (c_p - c_v)T$$

$$\beta = (h_L - c_p T)$$

we derive the temperature dynamics of the tunnel as

$$\dot{T} = K_L\left(\frac{\alpha+\beta}{\theta}\right)\left(\frac{1+t_m s}{1+t_G s}\right)e^{-\tau_L s}A_L + \frac{K_F}{K_M}\left(\frac{pM^2}{\theta(1+0.2M^2)^3}\right)\left(\frac{1+t_m s}{1+t_G s}\right)e^{-\tau_F s}N - K_G\frac{p\alpha}{\sqrt{T}\theta}\left(\frac{1+t_m s}{1+t_G s}\right)e^{-\tau_G s}A_G \tag{1}$$

where $\theta = W_G c_v + W_m c_m$

From the ideal gas law, the pressure of a confined gas is proportional to the mass of the gas and its temperature ($p \alpha W_G T$). After taking the appropriate derivatives and making substitutions, the time rate of change of pressure may be expressed as

$$\frac{\partial p}{\partial t} = \frac{p}{W_G}\frac{\partial W_G}{\partial t} + \frac{p}{T}\frac{\partial T}{\partial t} + \text{momentum effects}$$

Substitutions and manipulation yield the pressure dynamics for the tunnel:

$$\frac{\partial p}{\partial t} = K_L\left[\frac{p}{W_G} + \frac{p}{T}\frac{(\alpha+\beta)}{\theta}\left(\frac{1+t_m s}{1+t_G s}\right)\right]e^{-\tau_L s}A_L + \left[\frac{K_F}{K_M}\left(\frac{p^2M^2}{T\theta(1+0.2M^2)^3}\right)\left(\frac{1+t_m s}{1+t_G s}\right)e^{-\tau_F s} + \frac{DbpMs}{K_M\sqrt{T}}\right]N - K_G\frac{p}{\sqrt{T}}\left[\frac{p}{W_G} + \frac{p\alpha}{T\theta}\left(\frac{1+t_m s}{1+t_G s}\right)\right]e^{-\tau_G s}A_G \tag{2}$$

where $b = 0.197[1 - 7pM/T]$

Equations (1) and (2) permit the description of the temperature and pressure response characteristics of the gas in the tunnel due to the tunnel control inputs.

The last equation necessary for modeling the 0.3 m tunnel is for Mach number:

$$M = \frac{N}{K_M\sqrt{T}}\frac{e^{-\tau_a s}}{(1+t_p s)} \tag{3}$$

where $K_M = 597\ (1-0.3M)p^{-0.035}$, t_p is the plenum time constant, and τ_a is the acoustic time lag.

In matrix form these equations are

$$\begin{bmatrix}\dot{T}\\ M\\ \dot{p}\end{bmatrix}=\begin{bmatrix} K_L\cdot\left(\frac{\beta+\alpha}{\theta}\right)\cdot\left(\frac{1+t_m s}{1+t_G s}\right)e^{-\tau_L s} & \frac{K_F}{K_M}\cdot\left(\frac{pM^2}{\theta(1+0.2M^2)^3}\right)\cdot\left(\frac{1+t_m s}{1+t_G s}\right)e^{-\tau_F s} & -K_G\left(\frac{p\alpha}{\sqrt{T\theta}}\right)\left(\frac{1+t_m s}{1+t_G s}\right)e^{-\tau_G s} \\ 0 & \frac{e^{-\tau_a s}}{K_M\sqrt{T}(1+t_p s)} & 0 \\ K_L\left[\frac{p}{W_G}+\left(\frac{p(\beta+\alpha)}{T\theta}\right)\cdot\left(\frac{1+t_m s}{1+t_G s}\right)\right]e^{-\tau_L s} & \left\{\frac{K_F}{K_M}\cdot\left(\frac{p^2M^2}{T\theta(1+0.2M^2)^3}\right)\cdot\left(\frac{1+t_m s}{1+t_G s}\right)e^{-\tau_F s}+\frac{DbpMs}{K_M\sqrt{T}}\right\} & -\frac{K_G p}{\sqrt{T}}\left[\frac{p}{W_G}+\left(\frac{p\alpha}{T\theta}\right)\cdot\left(\frac{1+t_m s}{1+t_G s}\right)\right]e^{-\tau_G s}\end{bmatrix}\begin{bmatrix}A_L\\ N\\ A_G\end{bmatrix} \qquad (4)$$

The development of the tunnel multivariable model shown in Eq. (4) is described in detail in Refs. 1-3, while operational and physical characteristics of the tunnel are contained in Refs. 4 and 5.

In matrix format, the model outputs (temperature rate, Mach number, and pressure rate) are related through the complex dynamics of the system to the inputs (liquid valve area, fan speed, and gaseous valve area). Examination of the model shows it to be highly coupled and quite nonlinear in nature. Transport time delays have been incorporated into the model to account for the mean time between control input and response measurement. For example, the delay associated with the input of liquid nitrogen is the lag corresponding to the transit time from the injection valves to the screen section where temperature is measured. The mathematical model was programmed on a hybrid computer in order to provide a valid real-time interactive simulation of the 0.3 m tunnel dynamics. This simulation of the 0.3 m tunnel is used not only for studying the tunnel control process, but also interactively for operator training and control system hardware checkout. All nonlinear computations are performed in the digital section of the computer, while the analog portion performs the required integrations. The rate of update between the digital and analog computer systems is 25 Hz.

Until recently, manual control of the 0.3 m transonic cryogenic tunnel has been through a control panel. Operator controls consist of a fan speed control rheostat, liquid nitrogen injection valve, and gaseous nitrogen exhaust valve control stations. Displays of Mach number, Reynolds number, temperature, pressure, and drive-fan speed are provided on the control panel for setting and maintaining test conditions. Other displays include liquid nitrogen pump pressure, fan drive motor power, and digital valve status indicator lights. Under normal circumstances, two or three operators are used to control the tunnel test conditions. When using three operators, one controlling task is assigned to each. When two operators are used, one operator controls fan speed while the other regulates both liquid nitrogen injection and gaseous exhaust. A similar control panel and set of displays were developed for the hybrid computer simulation. Using this hybrid computer control panel, operator inputs are made through potentiometers which control the (simulated) liquid and gaseous nitrogen valve openings and the fan speed. The digital displays permit realistic simulation of tunnel operation including operator imposition of constraints such as maximum cool down rates or metal-to-gas temperature differences.

An important milestone completed during this research was the validation of the synthesized math model throughout the tunnel operational envelope. Table 1 shows the test conditions for validation, and a comparison between the transient responses at high and low temperature obtained from the 0.3 m tunnel and from the hybrid computer simulation of the tunnel are shown in Figs. 2 and 3. In the tunnel, the step increase in liquid nitrogen flow rate was achieved by pulsing the 6.25% flow element of the digital valve. Similarly, exhaust of gaseous nitrogen was accomplished by pulsing the 6.25% flow element of the digital exhaust valve. These inputs were simulated on the computer by an electrical pulsing subroutine. A 100 rpm step decrease in fan rpm provided the disturbance for the fan response data. In general, the agreement between the tunnel and simulator responses are excellent, and it is felt that the slight mismatch is due to inaccuracies in the liquid nitrogen flow rate measurement from the tunnel.

Table 1 Tunnel and simulator test conditions

No.	Total temperature, K	Test section Mach number	Total pressure, atm
1	100	0.3	1.57
2	100	0.6	1.57
3	100	0.9	1.57
4	100	0.3	3.00
5	100	0.6	3.00
6	100	0.95	3.07
7	100	0.3	5.00
8	100	0.6	5.00
9	100	0.9	4.93
10	200	0.3	1.57
11	200	0.6	1.50
12	200	0.9	1.57
13	200	0.3	2.65
14	200	0.6	3.00
15	200	0.9	3.00
16	200	0.3	5.00
17	200	0.6	5.00
18	200	0.9	5.00
19	275	0.3	1.57
20	275	0.6	1.57
21	275	0.75	1.57
22	275	0.3	3.00
23	274	0.6	3.00
24	275	0.75	3.00
25	275	0.3	5.00
26	275	0.6	5.00
27	275	0.8	5.00

Long-term quasisteady-state comparison of simulation to tunnel responses is illustrated by the cool down profiles shown in Fig. 4. As can be seen, there is good agreement between the data from the tunnel and the predictions from the simulator. These data were obtained by maintaining constant total pressure, fan speed, and liquid nitrogen injection valve

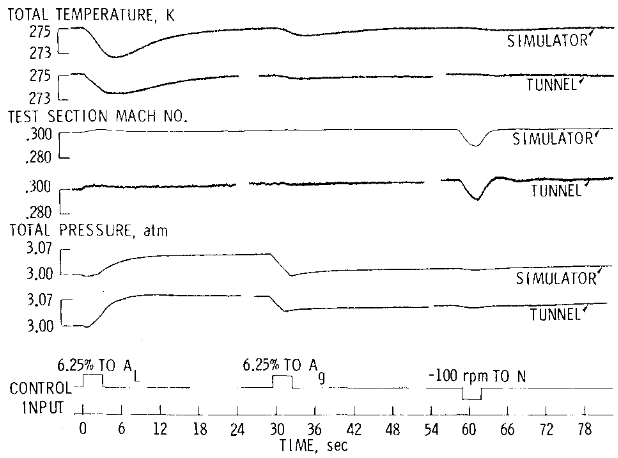

Fig. 2 Simulator and tunnel transient response data: $T=275$ K, $M=0.3$, and $p=3.00$ atm.

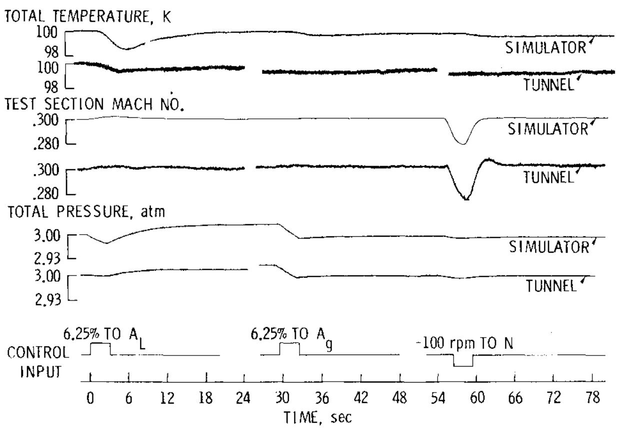

Fig. 3 Simulator and tunnel transient response data: $T=100$ K, $M=0.3$, and $p=3.00$ atm.

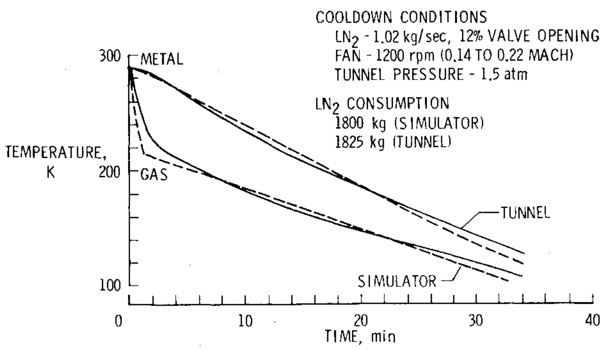

Fig. 4 Quasi-steady-state cooldown profile.

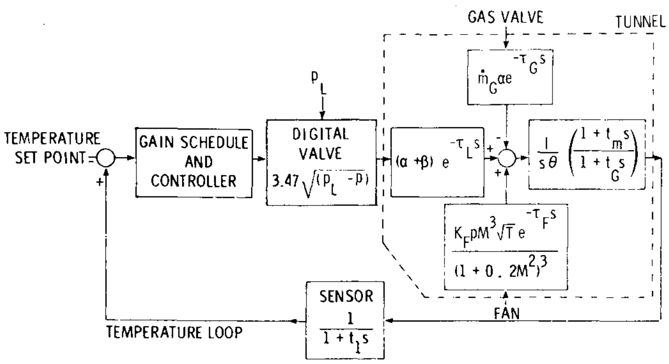

Fig. 5 Temperature loop schematic for 0.3 m tunnel control.

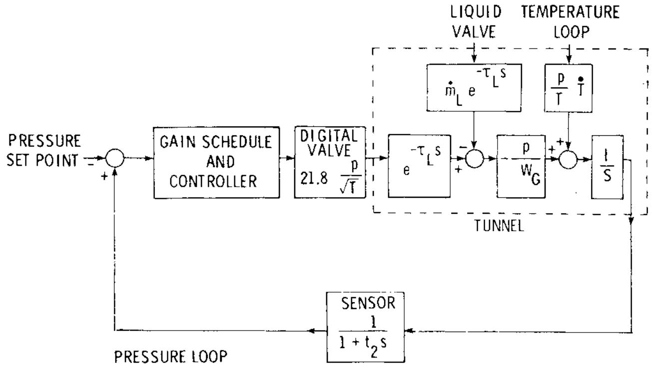

Fig. 6 Pressure loop schematic for 0.3 m tunnel control.

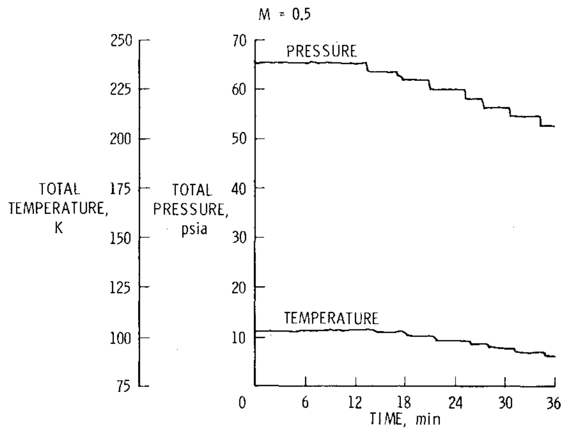

Fig. 7 Closed-loop performance of 0.3 m TCT to temperature and pressure setpoint changes.

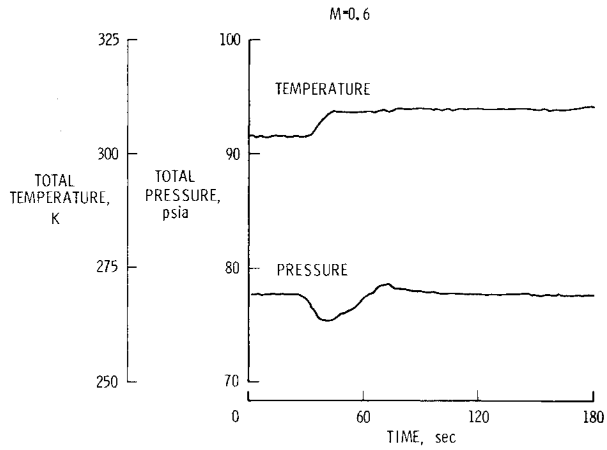

Fig. 8 Closed-loop transient performance of 0.3 m TCT to temperature setpoint change.

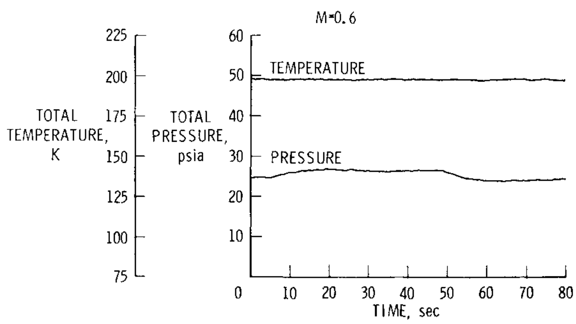

Fig. 9 Closed-loop transient performance of 0.3 m TCT to pressure setpoint changes.

opening. During cool down, Mach number varied from 0.14 to 0.22 because of the continuous reduction in temperature. It is apparent from these data that higher metal-to-gas temperature differences exist during the early stages of cool down as compared to later stages. The amount of liquid nitrogen consumed during cool down as computed by an integration technique in the simulator is within about 1% of the amount of liquid nitrogen used in the actual cool down of the 0.3 m tunnel.

With satisfactory model validation now considered complete, attention was directed toward the design of temperature and pressure feedback controllers. Schematic diagrams of the temperature and pressure closed-loop designs are shown in Figs. 5 and 6. The elements of these loop diagrams developed for the 0.3 m tunnel represent the dynamics of the digital valves, the process, and the measurement sensors. Precomputed gain scheduling derived using standard root locus techniques is incorporated in the simple proportional-integral-derivative controllers. Also shown in these figures are the influences of the liquid injection and gaseous valve inputs on the pressure and temperature processes, respectively. Information derived from the simulator studies was used for fine tuning and making the final gain selection for these control laws.

Culmination of this effort was realized after utilizing the proportional-integral-derivative controllers in dedicated microprocessors for closing the temperature and pressure loops in the 0.3 m tunnel. Tunnel closed-loop performance using the simulator designed feedback laws are shown in Figs. 7-9. The responses to numerous temperature and pressure setpoint changes for a constant Mach number can be seen in Fig. 7, while transient performance for small temperature and pressure changes is shown in Figs. 8 and 9. To date, the control laws implemented in the tunnel are able to maintain both temperature and pressure to within the selected design criteria of ± 0.25 K and ± 0.25 psia. There exists, however, a slight overshoot which is not totally undesirable since this enhances the speed of response. As found with the simulator, the tunnel settling times are about 25 s for small temperature and pressure setpoint changes which are considered satisfactory for closed-loop tunnel control.

Conclusions

The control system development for the 0.3 m cryogenic tunnel has progressed to the point that there exists a global math model that has been validated by comparison to experimental dynamic response data. This model has been computer programmed and interfaced to a control panel so that operator training and simulation studies can be conducted. Presently, the microprocessor-based control laws are able to maintain temperature to within ± 0.25 K and pressure to within ± 0.017 atm. It is anticipated that upon completion of installation of 16-bit analog-to-digital converters for the existing microprocessor, temperature and pressure should be maintained to within ± 0.10 K and ± 0.007 atm, respectively. All-in-all, these two control laws have yielded very good closed-loop experimental results. Future work will include further refinements to the math model by the use of identification techniques for more precisely determining tunnel parameters. Lastly, optimal control studies will be made in order to allow energy and time minimization in the operation of the tunnel.

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